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STRUCTURE OF METAMORPHIC ROCKS AT MINERAL KING CALIFORNIA

BY

M. N. CHRISTENSEN

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STRUCTURE OF METAMORPHIC ROCKS AT MINERAL KING, CALIFORNIA

BY

M. N. CHRISTENSEN

ABSTRACT

Isoclinally folded metasedimentary and metavolcanic rocks constitute a northwest trending septum between plutonic masses at Mineral King in the south-central Sierra Nevada. The contact with granitic rocks on the east side is discordant, that on the west side is concordant. Bedding in the metamorphic rocks forms major isoclinal folds with subhorizontal axes and nearly vertical limbs. The mean orientation of cleavages parallels the axial planes of these folds, but cleavage orientations fan slightly about vertical axes; consequently, intersections of cleavage with bedding have a variety of orientations and generally plunge steeply. The geometry of bedding-cleavage intersections indicates that cleavage formed after bedding was tightly folded. Small folds are parallel to lineations produced by bedding-cleavage intersections and may, therefore, have been indirectly produced by the same intersection. Because the orientations of linear structures are functions of relative orientations of bedding and cleavage, they do not necessarily have any direct kinematic significance.

Bedding in the less competent rocks has been transposed into lenticular lithologic layering, or foliation, by slip on cleavage. The foliated rocks are inferred to have deformed by a process akin to laminar slip on cleavage with strike-slip movements perpendicular to the vertical axis of cleavage intersections. As a consequence of the transposition of bedding, major folds formed by bedding tend to be obscured, or even obliterated, and a superficially homoclinal sequence of bedded and foliated rocks is produced. Pervasive disharmonic folding on all scales interrupts regular repetition of units by folding and thereby further obscures major fold patterns.

INTRODUCTION

Location and Problem

The Sierra Nevada of California is a large composite batholith within which lie isolated bodies of metamorphic rock. Contacts between plutonic and metamorphic rocks are grossly conformable with structures in the metamorphic bodies. Within many of the metamorphic masses lithologic units crop out as parallel bands. Foliation and bedding strike northwest, parallel to the range, and dip steeply. These metamorphic bodies provide the only remaining evidence of the stratigraphic and structural history of the Sierra Nevada before emplacement of the granitic rocks. The structural evolution of the metamorphic rocks, the extent to which deformation has modified stratigraphic relations, and the relation of the metamorphic structures to emplacement of the granitic rocks are all imperfectly understood. This study is an effort to improve understanding of these problems.

One of the metamorphic bodies occurs in the Mineral King district in the central, southern Sierra Nevada (fig. 1). The structure appears to be a vertical homocline composed of structurally concordant bedded and foliated rocks, surrounded by granitic plutons. Within this structure, compositional layering is lenticular on all scales, and foliated rocks contain pervasive, steeply plunging lineations and small folds. The relation of these small features to large structures is the major problem of structural interpretation. This problem is approached through detailed description and analysis of the structure. Because good expo-

Fig. 1. State of California, location of the Mineral King district.

sures are necessary for detailed structural work, mapping was limited to well-exposed areas comprising about thirty square miles in the northern half of the metamorphic mass. No attempt was made to carry this work into less-well-exposed areas in the southern part or at the extreme north of the metamorphic body. The general distribution of rocks in these areas was mapped by Knopf and Thelen (1905).

The description herein is arranged to emphasize features of the metamorphic rocks. The plutonic framework within which the metamorphic body lies is described first. Then the age, lithology, and structure of the metamorphic rocks are considered. Unconsolidated deposits, which appear on the map, are described elsewhere.[1]

Previous Work in the Area

The work of Knopf and Thelen (1905), in which they described the geomorphology, glacial geology, and bedrock geology, constitute the only previous systematic mapping of the Mineral King area. Their work was preceded by a report on prospects and mines by W. A. Goodyear in 1888, a report of Triassic fossils in

[1] M. N. Christensen, "Geologic Structure of the Mineral King Area, California" (Ph.D. dissertation, University of California, Berkeley, 1959).

the metamorphic rocks by H. W. Turner in 1893, and a brief general description of the area by A. C. Lawson in 1903. Subsequently, A. Pabst (1929) studied mafic inclusions in the granitic rocks near Eagle Lake, and C. Durrell (1940) collected fossils of Late Triassic age in the metamorphic rocks.

Acknowledgments

This work was undertaken as part of a program leading to the degree of doctor of philosophy at the University of California, Berkeley. I am especially indebted to Lionel E. Weiss and Alexander K. Baird for inspiration and criticism, and to G. H. Curtis, C. M. Gilbert, H. E. Hawkes, R. L. Langeheim, R. K. Smith, A. V. Cox, and J. G. Moore for aid and criticism at various stages of the study. Howard Hamman assisted in the field in 1958. I also express appreciation to the Geological Society of America, the National Science Foundation, and the University of California for financial assistance during the investigation.

THE PLUTONIC FRAMEWORK

The plutonic rocks that surround the metamorphic body range in composition from quartz diorite to granite. A small body of gabbro is enclosed within the metamorphic body.

Gabbro

Medium- to coarse-grained gabbro constitutes a long, lenticular, concordant body in the central part of the metamorphic mass. The gabbro has hypidiomorphic and allotriomorphic granular textures; plagioclase tablets have strong parallel preferred orientations. Along the margins the gabbro is sheared and has developed schistose and cataclastic textures. Plagioclase (An_{50} to An_{85}) and pale green amphibole are the major minerals. Biotite and epidote are abundant in some specimens. Augite, soda amphibole, and alkali feldspar occur sparsely. Accessory minerals in various specimens are apatite, sphene, hematite, magnetite, and sulfides. In the schists and cataclasites along the margins, fractured to granulated plagioclase tablets are suspended in a matrix of oriented biotite with subordinate chlorite, epidote, and calcite.

Quartz Diorite

Medium-grained, hornblende-biotite quartz diorite with a color index of 25 forms a stock on the northeast flank of the metamorphic body. The rock is massive and hypidiomorphic granular except in fine-grained, porphyritic border zones. It consists of plagioclase (An_{50}), biotite, hornblende, quartz, and minor alkali feldspar. The alkali feldspar and most of the quartz are interstitial; the biotite and hornblende are usually marginally altered to chlorite. Accessory minerals are sphene, apatite, zircon, and titaniferous magnetite. Intrusion breccias and dikes are common along the contacts, which transect metamorphic structures.

Granodiorite

Foliated, medium-grained, hypidiomorphic granular, biotite-hornblende granodiorite with a color index from 15 to 35 flanks the metamorphic body on the west.

Monoclinic alkali feldspar (2V=50°, Z=b) and plagioclase (An_{15} to An_{35}) are both prominently zoned. The alkali feldspar is rarely perthitic. Augite, partly altered to hornblende, occurs locally. Accessory minerals are sphene, apatite, zircon, magnetite, and pyrite. These rocks contain abundant ellipsoidal mafic inclusions. Aplites and pegmatites occur in variable amounts. These granodiorites are variable in texture and in proportion of minerals and may constitute several distinct plutons. Gradual transitions from one distinct type to another occur in some places; elsewhere sharp contacts can be mapped.

Planar preferred orientation of biotite and hornblende produces a primary foliation. Ellipsoidal inclusions are flattened parallel to the foliation, and the long axes of these ellipsoids have a vertical parallel preferred orientation. North of Eagle Lake the foliation forms swirls of irregular style with vertical axes.

The contact with metamorphic rocks is grossly conformable, but in detail it transects metamorphic structures. Foliation in the granodiorite parallels irregularities in the contact. Small-scale intrusion breccias occur in several places. A tongue of granodiorite extending into the metamorphic rocks east of Eagle Lake is partly mylonitized. South of the East Fork of the Kaweah River some fine, sharp-walled aplite veinlets that cross the metamorphic foliation are folded with axial planes parallel to the foliation. In the same outcrops, other fine aplite veinlets are straight and undeformed.

Granite

Massive, coarse-grained, hypidiomorphic granular, biotite-hornblende granite, with a color index of 5, flanks the metamorphic body on the east. Microcline perthite is the dominant feldspar. Feldspars are not zoned. Quartz has undulatory extinction. Chlorite replaces the edges of hornblende and biotite in some specimens. Accessory minerals include sphene, rutile, magnetite, apatite, zircon, and rarely fluorite. Inclusions are sparse but uniformly distributed. These rocks show little variation throughout the area mapped.

The contact with wall rocks transects metamorphic structures conspicuously. Coarse intrusion breccias occur in several places and are superbly exposed in the cliffs above Spring Lake. In many places grain size decreases within about 20 feet of the contact.

Emplacement of the Plutonic Rocks

The contacts of the gabbro body are poorly exposed, and little can be said about the mode of emplacement. The contact relations of the granitic masses indicate that they were mobile masses emplaced by intrusion, and that the quartz diorite was specifically magmatic. The granitic plutons all transect metamorphic structures, and all have intrusion breccias along their contacts. In addition, the quartz diorite is porphyritic along the contact, the foliation of the granodiorite parallels irregularities in its contact, and locally the granite tends to be fine-grained along its contact.

The sequence of emplacement is inferred from indirect evidence to have been, from oldest to youngest, (1) gabbro, (2) granodiorite, (3) quartz diorite, and (4) granite. The gabbro is inferred to have been emplaced after structural trends

were established but to have crystallized before the last deformation or stages of deformation because, first, it is concordant with metamorphic structures, and second, its margins are schistose and cataclastic.

The cross-cutting of metamorphic structures indicates that all the granitic plutons were emplaced after deformation of the metamorphic rocks. The granodiorite on the west side least conspicuously transects metamorphic structures, but schists along its contact have granoblastic matrices, suggesting that they recrystallized after all deformation stopped. The following evidence, however, suggests that some movement took place in the schists during emplacement of the granite: (1) folding of some fine aplite veinlets in the schists along the contact, and (2) mylonitization of the granodiorite tongue east of Eagle Lake. The granodiorite might have been emplaced at the very close of deformation, or, alternatively, emplacement of the granodiorite might have superposed some minor movements on previously deformed rocks.

The quartz diorite and granite both seem to have been emplaced some time after deformation of the metamorphic rocks because (1) they are sharply cross-cutting, (2) schistosity in the metamorphic rocks tends to be obliterated by hornfelsic textures along their contacts, and (3) their dikes in the wall rocks are straight-walled and undeformed, offset only by minor faults. The granite is believed to be younger than the quartz diorite because intrusion breccias along the margins of the granite contain blocks that were probably derived from the quartz diorite and because the configuration of the contacts at the north end of the map suggests a tongue of granite projecting into the quartz diorite. On the other hand, near the quartz-diorite contact with granite on Cliff Creek the quartz diorite contains some grapefruit-sized inclusions that resemble the granite. The relative ages of these two plutons, therefore, are not clearly established. Knopf and Thelen (1905, p. 239) concluded that the quartz diorite intruded the granite.

The ages of these plutonic rocks cannot be precisely determined from field relations. They intrude a metamorphic mass that contains Upper Triassic strata, and they are unconformably overlain by Quaternary deposits. Granitic rocks of the Sierra Nevada have traditionally been referred to the "Nevadan" orogeny, which has in turn been traditionally referred to the Late Jurassic. Curtis, Evernden, and Lipson (1958), however, on the basis of potassium-argon age determinations, concluded that the Sierra Nevada was affected by major intrusions in both the Late Jurassic and Late Cretaceous and that the granites of the high Sierra Nevada are principally of Late Cretaceous age. A sample of granite from Columbine Lake on the east side of the metamorphic body yielded a K–Ar age of 87 million years (G. H. Curtis, personal communication). The granodiorite of the west side, which has some synkinematic features, may fall in the group of Upper Jurassic intrusives.

AGE OF THE METAMORPHIC ROCKS

Fossils occur in a unit composed of sandstone and argillite hornfelses interbedded with marble. Fossils from this unit were assigned a probable Late Triassic age by Smith (1927, p. 9) and a middle Late Triassic age by Muller (in Durrell, 1940, p. 17). J. W. Durham has made preliminary identifications of fossils collected by

me and Roberta K. Smith. He tentatively assigned a late Karnian age to two localities and a Norian age to four other localities. These fossils are in the collections of the Museum of Paleontology, University of California, Berkeley. Details of the locations and contents of the collections are available in my unpublished dissertation.[2]

LITHOLOGY OF THE METAMORPHIC ROCKS

The metamorphic suite consists of tectonites (following usage of Sander, 1930, p. 62) and hornfelses of both sedimentary and volcanic derivation. These rocks are divided into two groups based on the predominance of primary stratification on the one hand and secondary foliation on the other. Bedded rocks locally contain textural evidence of stratigraphic sequence, but the over-all stratigraphic succession is not known. Deformation has profoundly modified the original thicknesses of stratigraphic units; discussion of the thickness of the metamorphic section is, therefore, deferred to page 184 under the heading "Interpretation of Structure."

Knopf and Thelen (1905, p. 242) noted that "lithologic units are relatively small.... The siliceous, calcareous, and argillaceous members are frequently stratified in rapid alternation, and, as a further complication, even the larger subdivisions are of strongly interdigitating habit and tend to thin out in the direction of their strike." Lenticularity characterizes the map, outcrops (pls. 1–4), and hand specimens. The units mapped are, in general, bulk assemblages of heterogeneous rocks. Proportions of different types of rocks vary locally within units. The precise location of contacts in many places is arbitrary because units interfinger along the contacts.

Discrepancies between the geologic map of this paper (in pocket) and that of Knopf and Thelen (1905, pl. 30) result from expectable differences between rapid reconnaissance and detailed mapping. Reconnaissance mapping of the highly lenticular metamorphic rocks is especially difficult. Knopf and Thelen provided an example of this problem; they described and illustrated (p. 253 and pl. 29B) sheared andesites on Crystal Creek, but on their map they showed only quartzite and limestone in that area.

Fine grain size of both the tectonites and the hornfelses hampers mineral identification. Groundmass material of most rocks is irresolvable under the microscope. Descriptions by Knopf and Thelen supplement those given here, especially with regard to accessory minerals and microscopic textural details.

Bedded Rocks

Sandstone and siltstone hornfelses (Map symbol: bsh).— Rhythmically bedded lithic wacke[3] and siltstone hornfelses occur in the southeast part of the area. These rocks occur in graded beds from one inch to three feet thick. Sand grains are angular to subangular and poorly sorted. Lithic fragments are fine-grained aggregates of quartz or quartz and feldspar. Granoblastic matrices of various specimens contain biotite, epidote, calcite, amphibole(?), and irresolvable felsic material. Minor amounts of pebble conglomerate and blastoporphyritic meta-andesite(?)

[2] Christensen, *op. cit.*

[3] Nomenclature from H. Williams, F. J. Turner, and C. M. Gilbert, *Petrography* (San Francisco: W. H. Freeman and Co., 1954), 406 pp.

are intercalated. Graded bedding in the sandstones on the anticline northwest of Florence Peak indicates that this unit underlies the following unit.

Argillite and sandstone hornfelses (Map symbol: msh).—Argillite and massive to thick-bedded quartz and arkosic wacke hornfelses occur with crystalline limestone in the eastern half of the metamorphic body. Sedimentary breccia occurs at the base of the unit; in places bedding in the underlying unit makes a large angle with this contact, which is probably an unconformity. Sand grains are angular to subangular and are composed predominantly of quartz, plagioclase, and alkali feldspar with minor lithic fragments. Granoblastic matrices consist of white mica, biotite, and irresolvable felsic material. Load casts, slump structures, and related sedimentary features are locally abundant in the sandstones; especially fine exposures of these features occur on the south side of Franklin Creek at an elevation of about 9,600 feet.

Where limy lenses are thick, they are foliated marble. The larger bodies of marble are separately mapped. Fossil localities occur along contacts between argillite and calcareous rocks. Subordinate amounts of slate and calc-silicate hornfels are intercalated with the clastic rocks.

Siliceous and calc-silicate hornfelses (Map symbol: sch).—Fine-grained, thin-bedded, siliceous and calc-silicate hornfelses with subordinate intercalated marble occur on both flanks of the metamorphic body. On the east side these rocks are finely laminated, and some siliceous volcanic rocks are intercalated. On the west side bedding is modified by structural surfaces in many places, some of these rocks are mylonitic, metachert is abundant, and some pelitic hornfelses are intercalated. Within a few hundred feet of the western contact with granodiorite, lime-bearing plagioclase takes the place of soda-plagioclase and dark green amphibole appears.

Foliated Rocks

Foliated rocks include slates, phyllites, fine-grained schists, and marble. Slates and phyllites were derived from clastic sedimentary rocks; schists were derived principally from volcanic rocks. Matrices of all these rocks are granoblastic. The hornfelsic textures tend to obscure foliate structures.

Slates and phyllites (Map symbol: sl).—Slate, phyllite, and phyllonite hornfelses occur in the central part of the metamorphic belt and structurally interfinger with bedded clastic rocks. Relic textures and compositions resemble both the thin-bedded and massive clastic rocks. Lithic fragments in sheared pebble conglomerates are flattened into lenses that stream around relatively undeformed quartz grains, which exhibit undulatory extinction and deformation lamellae. White mica and biotite are common in the matrix material along with calcite and irresolvable felsic and dark material. Hornfelsic textures obscure cleavage, which in some places is apparent only in weathered outcrops. Mylonite, marble, and meta-andesite(?) are sparsely intercalated.

White mica schists (Map symbol: ms).—Quartz-white mica schists occur on both sides of the metamorphic belt. Relic textures are locally preserved and indicate derivation from lithic, crystal tuffs and breccias with subordinate flow rocks. Original composition was probably rhyodacitic. Where relic textures are preserved, lithic fragments in the tuffs include porphyritic dacite(?), feldspathic

sandstone, and argillite. Clusters of andalusite in the strongly deformed schists were probably derived from pelitic fragments in the pyroclastic rocks. Crystal fragments in the pyroclastic rocks include idiomorphic quartz, oligoclase, and alkali feldspar. In strongly foliated pyroclastic rocks quartz crystals are notably more deformed than feldspar crystals. The feldspars retain their idiomorphic, igneous habit, often without marginal granulation, in the same rocks in which quartz clasts have strong undulatory extinction and deformation lamellae, and are extensively granulated.

The mineral composition of the matrices of these rocks varies with the degree of deformation. The matrix of undeformed pyroclastic rocks is usually quartz and alkali feldspar with subordinate biotite. In even slightly foliated rocks the matrix consists of quartz and white mica with subordinate biotite. Minor amounts of sandstone and calc-silicate hornfelses and slate are intercalated with the metavolcanic rocks.

Plagioclase-biotite schists (Map symbol: bs).—Blastoporphyritic plagioclase-biotite schists occur abundantly on the east side of the metamorphic belt and sparsely on the west. Locally preserved relic textures suggest that the schists were derived from volcanic flows with subordinate amounts of tuffs, breccias, and sandstones. Original composition of the volcanic rocks was probably andesitic.

Blastoporphyritic feldspars of igneous habit survive in many of the schists. Oligoclase flecked with calcite is abundant. Where calcite does not occur the plagioclase is andesine or labradorite. Original mafic minerals have been destroyed. Biotite is abundant. Epidote, chlorite, and blue-green amphibole occur sparsely.

Fragments in the pyroclastic rocks are predominantly porphyritic volcanic rock with subordinate amounts of quartzite and pelite.

Biotite schists with aluminous hornfelses (Map symbol: sh).—Biotite schists and aluminous hornfelses are intercalated in layers several tens of feet thick along the east side of the metamorphic belt in the vicinity of Mineral Peak. In the schists both blastoporphyritic and relic pyroclastic textures are common. Original composition of these rocks was probably andesitic. Idiomorphic plagioclase and alkali feldspar lie in a schistose matrix of biotite and felsic material. Fine-grained hornfelses contain abundant andalusite and micas. Tourmaline occurs with biotite in black, carbonaceous hornfelses near Crystal Lake.

Marble (Map symbol: m).—Marble occurs as lenses in several of the units. Where it forms bodies of sufficient magnitude, it has been separately mapped. It varies from fine- to coarse-grained and from massive to strongly foliated, with grey and white laminations. The larger lenses tend to be more coarse-grained and more strongly foliated. Thin lime beds intercalated with other rocks are usually crystalline limestone. Locally marbles are flecked with prisms of actinolite or small plates of a micaceous mineral. Along contacts with plutonic rocks the marbles are coarse-grained, massive, and dazzling white. Small pods of skarn occur along the intrusive contacts.

Conditions of Metamorphism

Tectonite fabrics are products of dynamic metamorphism. Hornfelsic fabrics are products of contact metamorphism. Contact metamorphism is inferred to have either followed or outlasted deformation because (1) matrices of schists are grano-

blastic, and (2) foliation is obliterated by hornfelsic fabrics adjacent to the granite contact on the east.

The mineral assemblages quartz–albite–epidote–(micas), quartz–albite–muscovite–biotite, and albite–epidote–actinolite–chlorite–quartz are common in rocks of appropriate compositions through most of the area and belong to the albite-epidote hornfels facies (Fyfe, Turner, and Verhoogen, 1958, p. 203). Within 500 feet of the granodiorite contact, lime-bearing plagioclase and dark green hornblende take the place of albite, and pale, blue-green, fibrous amphibole, respectively, in rocks of appropriate composition. These changes correspond to an increase in grade to the hornblende hornfels facies and persist to the granitic contacts.

STRUCTURE

Mesoscopic[4] structures, which can be observed directly in outcrops, are described before macroscopic structures, which are determined indirectly by mapping. Because of the fine grain size of the hornfelses, microscopic petrofabric was not studied. Lower-hemisphere equal-area projections are used for description of geometry of structures. To facilitate discussion of the diagrams, standard nomenclature (Sander, 1948, pp. 132–146; Weiss, 1957, p. 587) is followed: πS is the pole of a plane; β is a line of intersection of two or more surfaces. If πS points spread in a girdle, β is the pole of the girdle. In folded structures, β is the fold axis. The "fold axis" is thought of as a generator line of a cylindrical structure—having orientation but not position (see McIntyre and Christie, 1957, pp. 645–646).

The equal area diagrams are contoured at 1, 9, 17, and 25 per cent of points per 1 per cent area. A "0" contour is also shown. This line delimits the area within which all the plotted points lie; if any part of a standard 1 per cent area counter lies outside this line, no points fall within the counting area.

Mesoscopic Structure

Orientations of structural elements of individual folds and continuous outcrops were studied by means of πS diagrams and equal-area plots of lineations. For example, elements of a fold in foliated rocks include the folded form surface, cleavage, and lineations. However constant the orientations of cleavage and lineation are within the field of a mesoscopic fold, they nevertheless vary by measurable amounts; therefore, on many mesoscopic structures, multiple measurements were made of all structural elements and orientations were studied on equal area plots. Approximately forty mesoscopic folds were studied in this detail; in each fold the preferred orientation of lineations and the separate β's for folded surfaces and for cleavage coincided.

In strongly foliated rocks folds are defined by faint composition layers that cross the foliation (fig. 2). Such rocks do not break along the folded form surface, orientations of the folded surfaces commonly cannot be measured, and the orienta-

[4] Weiss (1957, p. 577) suggests definitions as follows: (1) *microscopic*—the field of a thin section; (2) *mesocopic*—field ranging from a hand specimen to a single continuous exposure; (3) *macroscopic*—fields of any size containing discontinuously observable structures: the structures are determined indirectly.

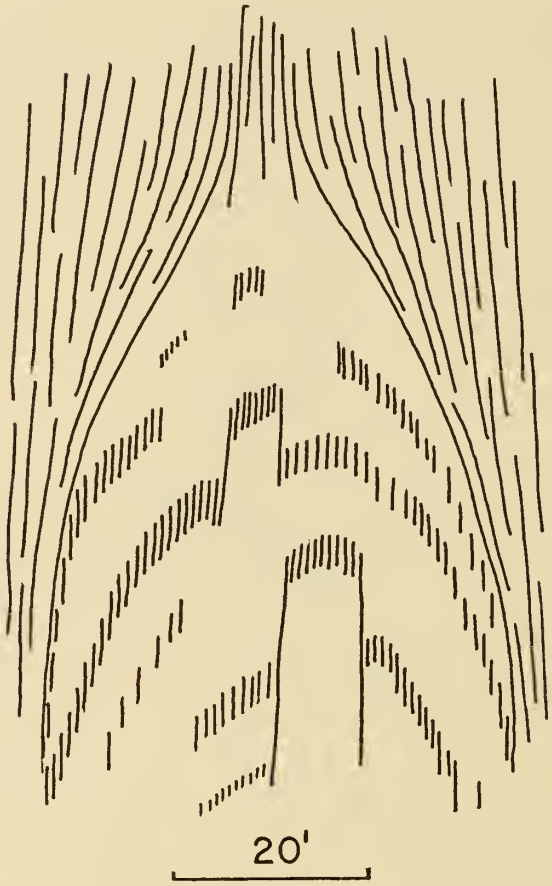

Fig. 2. Faint relics of compositional layers (bedding ?) cross axial plane foliation and define a fold in slate-hornfels. Orientations of the folded layering cannot be measured because surfaces are obliterated. Intersection of relic layers produces compositional streaks on cleavage. About 0.4 mile northeast of Eagle Lake.

tion of the fold axis, therefore, cannot be determined directly. In every fold of this type that was studied, β for cleavage coincided with the preferred orientation of lineations, and this direction was inferred to be that of the fold axis.

SURFACES

Primary stratification and secondary foliation are both present. In favorable exposures it is apparent that foliation consists of two contrasting kinds of surfaces: lenticular lithic layering and cleavage. Transitions occur between bedding and lithic layering (pp. 170–178).

Bedding occurs in units of mappable size and also in isolated small folds in foliated rocks. Common thicknesses of beds vary from one millimeter to about 15 centimeters. Beds maintain uniform thicknesses over the lateral extent of indi-

vidual outcrops. Degree of preservation of bedding is a function of rock type: bedding occurs commonly in metacherts, siliceous and calc-silicate hornfelses, and in thin-bedded clastic rocks where sandstones predominate; it is rare in carbonate, pelitic, and volcanic rocks.

Lithic layering occurs in foliated rocks and is formed by thin, streaky, lithic lenses (pls. 1, *b*; 2, *b;* 3, *b;* and 4). Layers are on the order of one millimeter thick in micaceous rocks; in siliceous rocks they may be a few centimeters thick. Along the strike of the layering, individual lenticles thin rapidly and pinch out, as do layers of mappable dimensions. The aspect of a large exposure from a distance strikingly resembles that of a hand specimen of the same rock at close range.

Cleavage is a penetrative surface of breakage in foliated rocks. It is rarely or only incipiently developed in bedded rocks, with the exception of slate partings in metacherts. It is usually nearly parallel to lithic layering. In many exposures cleavage and lithic layering cannot be differentiated as separate surfaces but together define the "foliation." Foliation can be seen to consist of cleavage and subparallel, but intersecting, lithic layering in outcrops where (1) joints break nearly perpendicular to the intersection of cleavage with lithic layering, (2) the joint surfaces are smooth, and (3) the joint surfaces are so weathered as to bring out subtle lithic layering. In strongly foliated rocks the angle between cleavage and lithic layering is so acute that favorable joints are essential in order to differentiate the surfaces. Cleavage is the surface measured in the field and plotted in πS diagrams for foliated rocks because it is the principal breaking surface in the rocks.

LINEAR STRUCTURES

Bedded rocks without cleavage are devoid of linear structures. Where both cleavage and bedding are present, rocks contain linear structures produced by their intersections. The predominant linear structures in foliated rocks, however—biotite trains and elongate patches of argillaceous material—are not obviously formed by intersections of surfaces. But in those outcrops where cleavage and lithic layering can be distinguished as separate elements of "foliation," the trains of biotite and elongate argillaceous patches can be seen to be produced by the intersection of lithic layering with cleavage. These lineations, therefore, are fundamentally similar to rod structures produced by intersection of bedding and cleavage. In the strongly foliated rocks, the angle between sets of surfaces is so small as to be almost imperceptible. Other linear structures are preferred orientations of elongate pebbles and minerals, rod structures, and wrinkled cleavages. In a given outcrop all these linear structures have parallel preferred orientation.

On the scale of hand specimens or small outcrops the lineations can be seen to indicate the direction parallel to which relatively long straight lines can be laid without crossing structural or compositional surfaces. Direction of continuity of the fabric on a larger scale was studied by means of πS diagrams of surfaces which swing around large lithic lenses in extensive, continuous outcrops (fig. 3). For every lens studied in this manner, β for the πS girdle coincided with the preferred orientation of directly measurable lineations in the outcrop. This direction is likely to be that of the long axis of large lenses in foliated rocks. Extrapolation to direction of continuity of fabric on a still larger scale does not seem justified

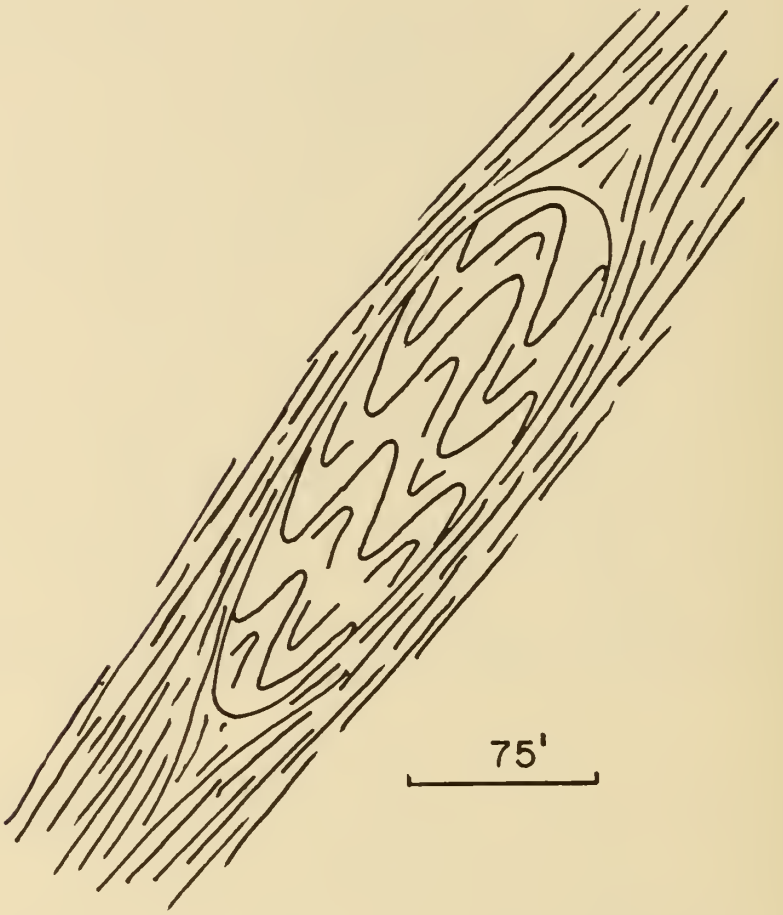

Fig. 3. Tightly folded bedding in sandstone lens in slate. Section drawn perpendicular to fold axes and to inferred long dimension of sandstone lens. Northwest of Farewell Gap at about 10,000 feet.

FOLDS

Most mesoscopic folds have amplitudes of a few feet, though the range in amplitude is from an inch or less to over one hundred feet. Styles of folds vary with rock type, but orientations of fold axes, axial planes, and lineations are independent of rock type. Lineations in all mesoscopic folds are formed by intersection of bedding or lithic layering with cleavage, and are parallel to the fold axes. Only one plane of symmetry is present in the fabric. This plane is perpendicular to the lineation, and the lineation is, therefore, a B symmetrologic axis on a mesoscopic scale. Representative folds from well-exposed localities are described in the following pages.

Folds in calc-silicate rocks.—A large mesoscopic fold about three-tenths of a mile north of Eagle Lake (fig. 4) is defined by a contact between calc-silicate hornfels and slate hornfels. Because this contact is indistinct, its orientations can-

Fig. 4. Map of nearly vertically plunging isoclinal fold. Dismembered folds, shown in calc-silicate rocks, are schematic representations of folds shown in plate 1, *a*. In adjacent slates bedding has been obliterated and transposed into lenticular lithic layering subparallel to cleavage. About 0.3 mile northeast of Eagle Lake.

not be measured. Lineations, small folds, and β of the πS girdle for cleavage all plunge about 80° to the west, and this is inferred to be the direction of the fold axis. The map is approximately a profile view of the fold. Bedding is tightly folded where it crosses cleavage at a large angle on the nose of the fold in the calc-silicate hornfels (pl. 1, *a*). It is partially disrupted by slip on cleavage. On the limbs, where bedding crosses cleavage at a small angle, beds are disrupted and fragments are rotated and flattened to form lenticles, or lithic layering subparallel to cleavage (pl. 1, *b*); relics of small asymmetric folds with one short limb are present. The dextral or sinistral sense of these small folds (see White and Jahns, 1950, p. 197) changes from limb to limb of the large fold as would be expected for drag folds. Complex folding within the calc-silicate rocks compared with simple folding of the main contact indicates disharmonic folding on the scale of this exposure.

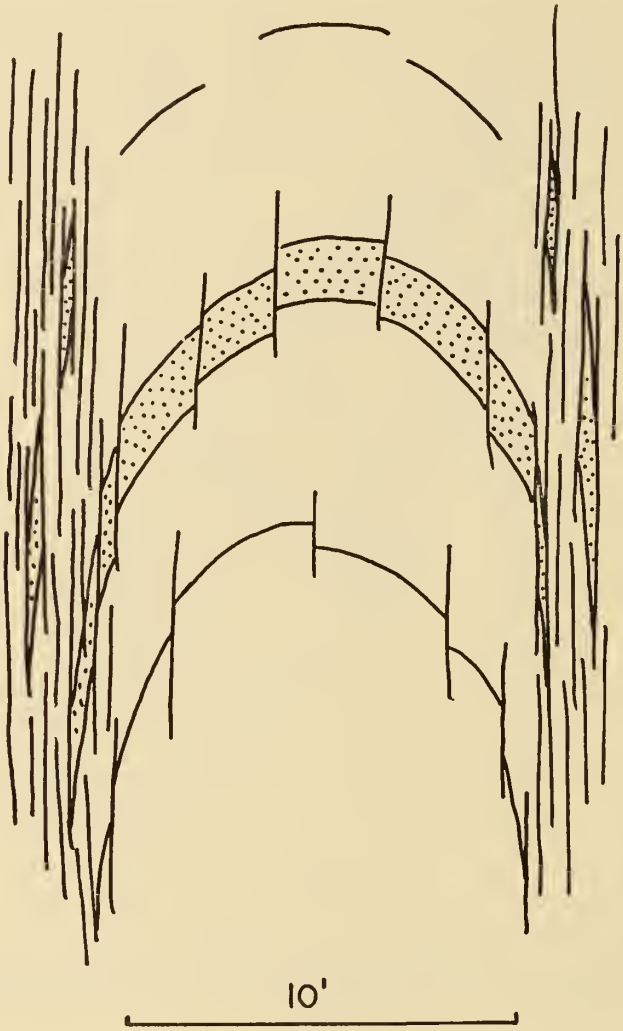

Fig. 5. Profile of fold in sandstone and siltstone hornfels. Lithic layering is subparallel to cleavage on the limbs of the fold. Both dextral and sinistral senses of slip occur along cleavage South side of Franklin Creek at about 9,600 feet.

Surfaces within either the calc-silicate or slate-hornfels do not indicate the large fold because (1) beds in the calc-silicate rocks are disrupted and complexly folded and (2) foliation in the slate hornfels constitutes an isoclinal or homoclinal sequence in which folding is not apparent. The distinctive lithologic contrast between calc-silicate hornfels and slate-hornfels is critical for recognition of the fold.

Folds in metasandstone.—On the south side of Franklin Creek, folds in bedded sandstone and siltstone hornfelses plunge 50° to 55° to the northwest (fig. 5). On the hinges of the folds, beds are offset across widely spaced, incipient axial plane

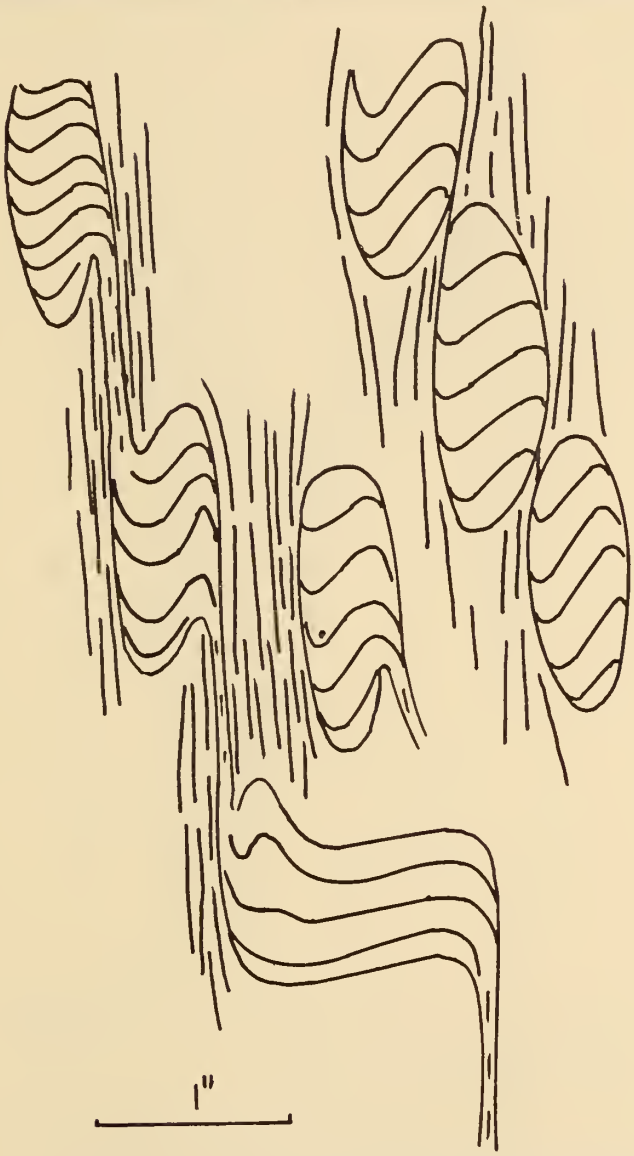

Fig. 6. Sandstone beds disrupted across shear zones on cleavage in siltstone. Section perpendicular to intersection of bedding and cleavage, so that these elliptical pods are cross sections of long rods. Laminations in the rods are folded with axial planes parallel to cleavage and fold axes parallel to the bedding-cleavage intersection. South side of Franklin Creek at about 9,600 feet.

cleavage (pl. 2, *a*). On the limbs of the folds, beds are disrupted by slip on closely spaced cleavage; fragments of beds are rotated and flattened until they form thin lenses, or lithic layering, subparallel to cleavage (pl. 2, *b*). On the noses of the folds, intersection of bedding with incipient cleavage produces compositional lineations, on cleavage, parallel to the fold axes. On the "sheared out" limbs, lineations also parallel the fold axes; these lineations appear on cleavage as streaky,

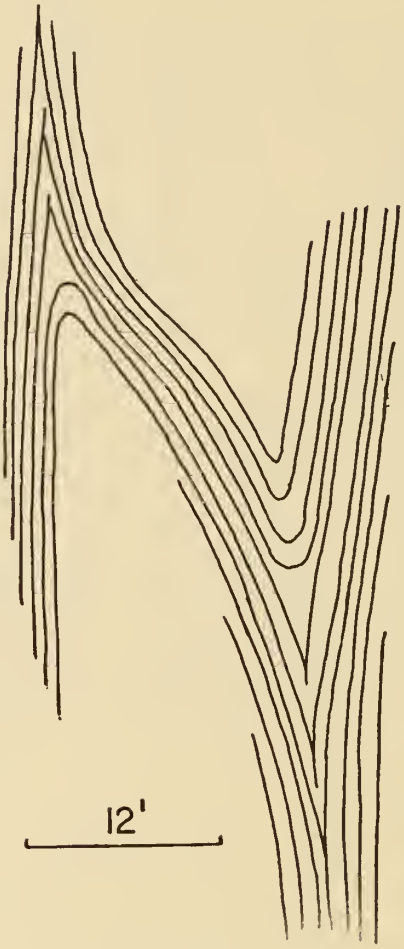

Fig. 7. Profile of isoclinally folded metachert with slate partings, from large chert mass in slate. Axial planes are parallel to cleavage in adjacent slates. Northwest side of Vandever Mountain at about 9,600 feet.

lithic smears which do not resemble original bedding-cleavage intersections. On the limbs of the folds bedding is transposed into lenticular lithic layering, which intersects cleavage to produce streaky lineations.

In the intermediate stages of transposition of bedding, before continuity of beds is completely destroyed, sandstone beds in slate are nearly disrupted across zones of closely spaced cleavage (fig. 6). These shear zones separate rods of laminated sandstone devoid of cleavage. Laminations within the rods are folded with axial planes parallel to cleavage and axes parallel to the intersection of bedding and cleavage. In more strongly foliated rocks, where continuity of bedding is completely destroyed, bedding is locally preserved and isoclinally folded in lenticular masses, which may be quite large (fig. 3). The long axes of lenses, on all scales, and of folds within them, are parallel to streaky lineations in surrounding foliated rocks. All of these linear structures are probably produced by modification of

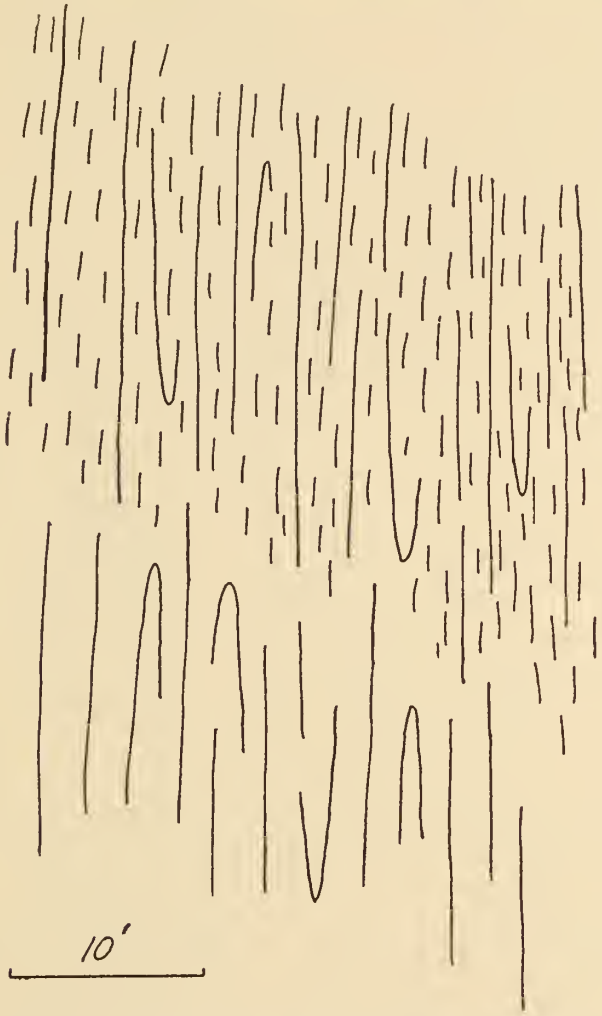

Fig. 8. Disharmonic folding along contact between two varieties of slate hornfels. Bedding nearly obliterated by transposition to lithic layering. Only a few hinges of tight folds remain. About 0.6 mile west of Mineral King village.

original intersections of bedding and cleavage. The contacts of the lenses are less intricately folded than are layers within the lenses. The structures are, therefore, disharmonic, and these contacts are important surfaces of discontinuity which separate different kinds of rocks which have different styles of structures but common symmetry.

Folds in metacherts.—In White Chief Bowl, metacherts with slate partings are isoclinally folded (fig. 7). Many beds are fractured in the tight hinges. The limbs are parallel to foliation in surrounding slates. Folding is disharmonic. Isoclinal forms are associated with more irregular and open folds, the limbs of which may be sheared off on surfaces parallel to the axial planes (pl. 3, *a*) to form a lithic layering composed of lenticular fragments of chert beds (pl. 3, *b*).

Fig. 9. Disharmonic folding in quartz–white-mica schist. Isoclinal folds sheared off on limbs and associated with folds of irregular form. South side of Monarch Creek at about 8,800 feet.

Wherever fractures or incipient cleavage cross chert beds, pelitic material from the slaty partings is smeared along the surfaces. These fractures or incipient cleavage constitute a family of planes with the same zone axis as the folded bedding and, therefore, intersect bedding and each other in lines parallel to the fold axis. These intersections appear on bedding surfaces of chert as lines of argillaceous material or trains of biotite.

Where slaty partings are thin, bedding is a smooth, regular, well-preserved surface. Where interbedded slates are thick, however, chert beds are disrupted by

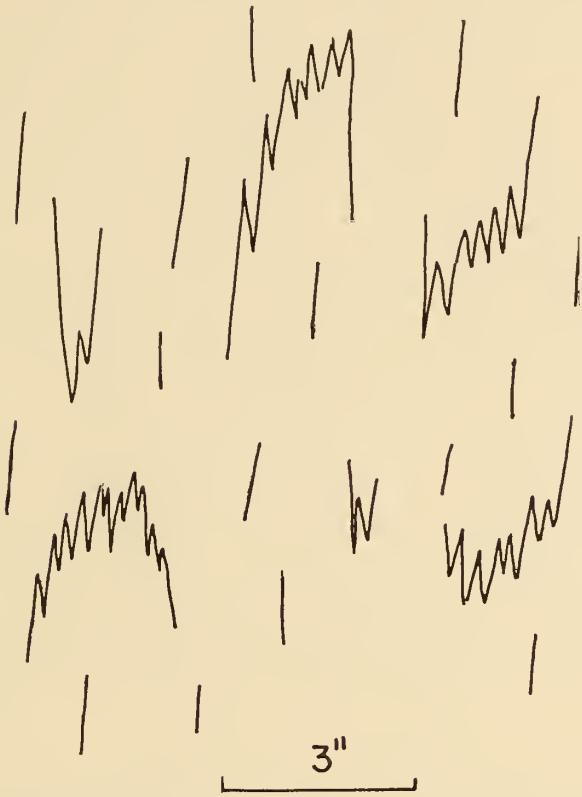

Fig. 10. Isoclinally folded shreds of disrupted beds (?) in quartz–white-mica schist. South side of Monarch Creek at about 8,800 feet.

slip on transecting cleavages (pl. 3, *a*). Where slaty material is predominant, chert beds are sliced, by slip on cleavage, into tectonic breccias consisting of long chert rods, which are equidimensional and angular in sections perpendicular to the fold axis, in slate matrix.

Folds in slates and mica schists.—Foliation in slates and mica schists constitutes a uniform homoclinal sequence in which both bedding and mesoscopic folds are rare. The presence of cleavage and lenticularity of lithic layering are the principal indications of intense deformation. The few folds detected were dimly apparent on joint surfaces perpendicular to lineations, and then only on joints so weathered as to bring out faint compositional layers. The forms of the folds are indicated by the faint compositional layers that cross foliation (fig. 2). Since all measurable surfaces are parallel to the axial surfaces, the orientation of a fold axis can be inferred only from orientations of lineations and β for cleavage.

Disharmonic folding is locally apparent. In a few places contacts transgress foliation (fig. 8); faint relic hinges of small isoclinal folds indicate complex deformation of rocks on either side of the contact. Locally in mica schists isoclinal folds are sheared off on the limbs and associated with more open folds of irregular form (fig. 9).

More commonly only faint shreds of cross-cutting layers (fig. 10) indicate the former presence of nearly obliterated compositional layers. Such shreds usually occur as local concentrations in foliated rocks. These concentrations are thought to represent hinge areas of obliterated folds because bedding tends to be best preserved in hinge areas, where it crosses cleavage at a large angle.

Augen mylonites occur along the contact between slates and white mica schists west of Timber Gap. Lamination in the mylonites is produced by transposition of bedding. Toward the mylonite zone isoclinal folds in slates are progressively disrupted by slip on cleavage; the fabric finally becomes very regular with scattered knots of quartz and feldspar (pl. 4, *a*). Adjacent to the mica schists, which are metavolcanic rocks, the mylonites contain lenses of blastoporphyritic metavolcanic rock. Lineations are parallel to hinges of folds in slates and are inferred to be relics of bedding-cleavage intersections.

Folds in carbonate rocks.—Beds of crystalline limestone in massive clastic rocks outline tightly appressed folds with amplitudes of one hundred feet or more. Wherever carbonate rocks predominate in a folded section, they are foliated marbles within which beds of clastic or calc-silicate rocks have been disrupted and transposed to form lithic layering parallel to axial surfaces of folds (pl. 4, *b*). In thick sections of marble the foliation is intricately folded. Gray and white laminations in marble intersect cleavage and thereby produce lineations characterized by faint color streaks on cleavage. These lineations are parallel to relic hinges of folds and to long axes of lenses of disrupted clastic beds in the marble.

Macroscopic Structure

The bedded and foliated rocks form a superficially homoclinal sequence that strikes northwest and dips nearly vertically. In the bedded rocks major isoclinal folds with rather gentle plunges are apparent. Secondary surfaces in the foliated rocks are parallel to axial surfaces of isoclinal folds in the bedded rocks, and, with one exception, major folds are not apparent; that is, the foliated rocks appear to be homoclinal rather than isoclinal.

In bedded rocks.—Macroscopic folds of tightly appressed, nearly isoclinal form are mapped in all the bedded rocks. Traces of axial surfaces of these folds are shown on the geologic map west of Monarch Lake, northwest of Florence Peak, and northwest of Bullfrog Lake. The axial surfaces of these folds are vertical. Plunges generally vary from 0° to 20°, though the anticline northwest of Florence Peak plunges 55° to the northwest. The half wavelengths of these folds range from about 1,200 feet to 2,000 feet.

Disharmonic folding on a major scale can be demonstrated on the anticline northwest of Florence Peak because its plunge is constant, at 55°, from Florence Peak northwest to the vicinity of Franklin Creek. In the area of constant plunge it is possible to construct a profile perpendicular to the fold axis (fig. 11) following the projection described by Argand (1911, pls. II and III), Wegmann (1929, pp. 103, 107) and McIntyre (1951, p. 15). The form of the fold is recognizable only in the thin-bedded clastic rocks and in the basal conglomerate of the overlying unit. In the overlying, thicker-bedded rocks, bedding is discontinuous and forms a lenticular isoclinal sequence. The form of the fold is obliterated in these

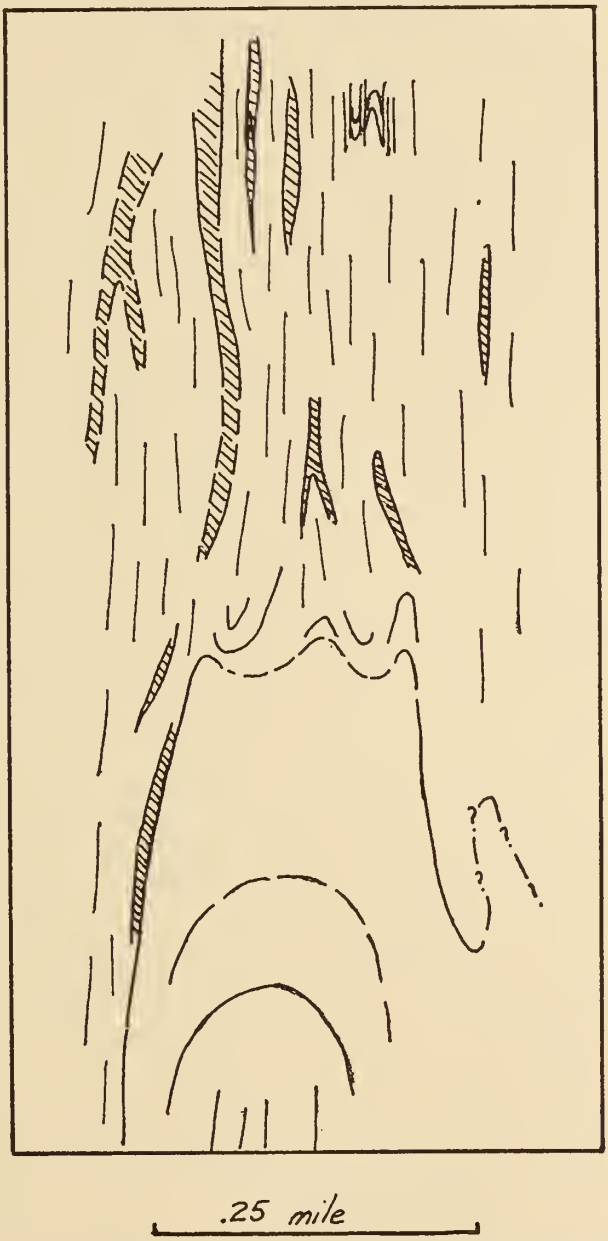

Fig. 11. Profile perpendicular to axis (plunging 55°, N15°W) of anticline northwest of Bullfrog Lake. In the core of the fold are thin-bedded sandstone and siltstone hornfelses. Outside are thick-bedded sandstone and argillite hornfelses. Slant-lined lenses are marble and crystalline limestone.

rocks but is reflected in plunging mesoscopic folds in sandstones on Franklin Creek (see p. 172, and upper-right center of fig. 11). These features on a macroscopic scale are strikingly similar to mesoscopic features in folded cherts (see p. 175, fig. 7, and pl. 3).

The syncline northwest of Bullfrog Lake also resembles in style folds in metacherts. Along some traverses it is truly isoclinal. In the sharp hinge area beds are broken and lie parallel to the axial surface or bedding becomes indistinct. Detection of the fold, therefore, depends on favorable exposures in the few critical areas where bedding still swings around the hinge.

No macroscopic folds are shown in the bedded rocks running north from Franklin Creek along the east side of the East Fork of the Kaweah River. These rocks are thick-bedded to massive clastic rocks in which folds are hard to detect. Wherever distinctive beds occur, however, mesoscopic isoclinal folds are apparent, some with amplitudes over one hundred feet.

In foliated rocks.—The only macroscopic fold in foliated rocks is located north of Franklin Creek where marble wraps around the south end of a white mica schist unit and forms a vertically plunging fold. Small folds resemble in style the major fold. Lineations and folds, from the scale of hand specimens to that of the entire fold, are paralled. The fold form is obliterated in the white mica schists which constitute an isoclinal foliated sequence.

The rest of the foliated rocks constitute a homoclinal sequence in which no macroscopic folds are apparent. Plot 1 of figure 12 is a πS diagram of 255 cleavages; these measurements are distributed with approximately equal frequency of occurrence in foliated rocks throughout the area. (Orientations of structures in rocks on Mineral Peak and north of Glacier Pass are not included in this plot for reasons discussed at the end of this section.) The β axis of the πS girdle is the axis about which cleavage orientations vary. This "cleavage axis" is essentially vertical. The cleavage axis was detected only through use of πS diagrams; it is not apparent in the field. Plot 2 of figure 12 summarizes orientations of 215 linear structures throughout the area and indicates that these are statistically parallel to the cleavage axis. Orientations of lineations were measured by trend and plunge in order that they be independent of measurements of cleavage orientations. Orientations of small folds are plotted together with lineations because these two kinds of structures are parallel in any given outcrop. Wherever bedding is locally preserved in the foliated rocks, it is folded about steep axes which are parallel to cleavage axes and lineations in surrounding foliated rocks.

The variation in orientations shown in plots 1 and 2 is not homogeneously distributed through the foliated rocks, but rather is distributed inhomogeneously through domains within which variation is more restricted. For example, plot 3 shows lineations and πS in a domain in the vicinity of Timber Gap; limits of this domain are shown on the sketch map of figure 12. In this area lineations form a tight cluster plunging southeast; β of the πS girdle falls within the cluster of lineations. In an adjacent area to the east (fig. 12, plot 4), lineations plunge northwest and β of the πS girdle falls within the cluster. In each of these areas the orientations of the cleavage axis, β, and lineations vary together.

Relatively homogeneous domains occur in the rest of the foliated rocks, but domains as homogeneous as that shown in plot 3 generally have dimensions of only a few hundred feet. In general, the smaller the domain, the tighter the cluster of lineations. In each case and on every scale from that of individual outcrops to that of the entire area, the orientations of the cleavage axis and the lineations vary

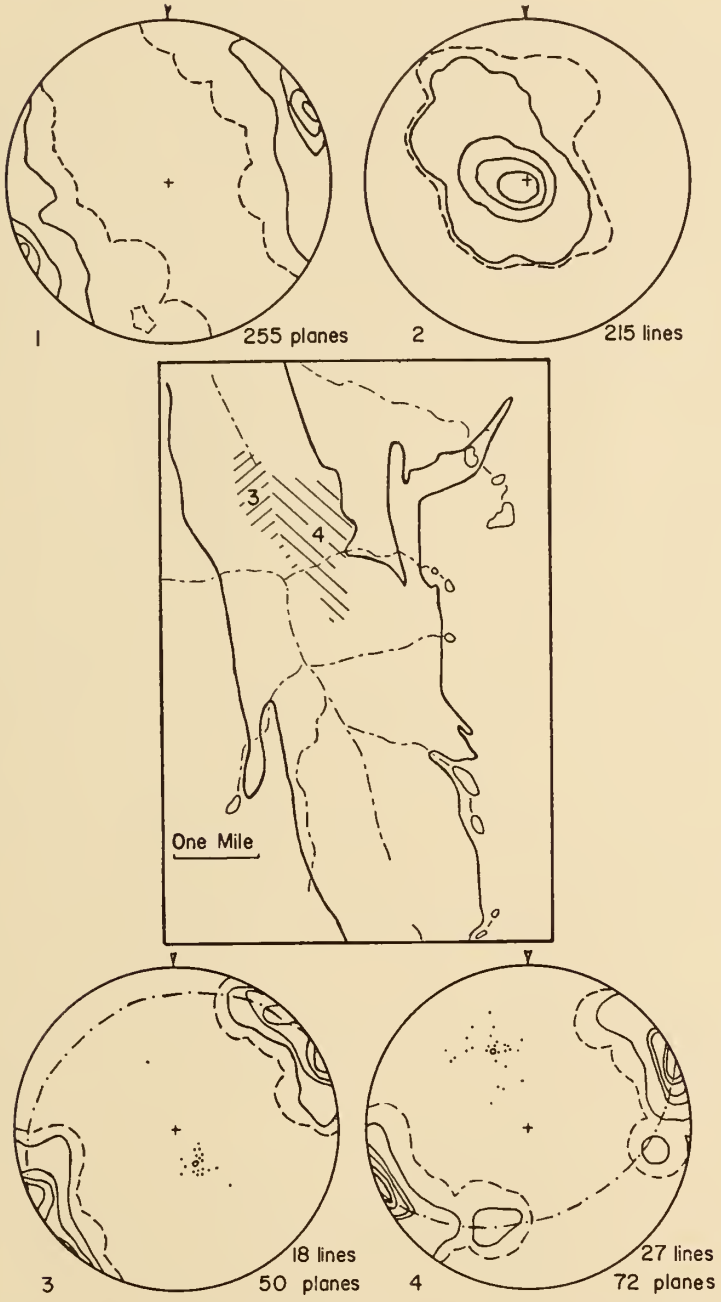

Fig. 12. Macroscopic geometry of the foliated rocks. Plots 1 and 2: geometry of foliated rocks throughout the map area. 1, poles of cleavage; 2, lineations. Plots 3 and 4: geometry of homogeneous domains within the foliated rocks. Extent of the domains indicated on the sketch map. Poles of cleavages are contoured; lineations plotted as points; β indicated by small circle in cluster of lineations. Lower hemisphere equal area projections. Contours: "0", 1, 9, 17, and 25 per cent, per 1 per cent area. (See text p. 167.)

together. The scatter of plots 1 and 2 summarizes variation between domains rather than within domains.

The significance of these diagrams is open to some questions. The first question concerns the significance of and method of determining β of the πS girdle of a nearly isoclinal structure. A discussion by Kamb (1959, p. 1909) shows that it is desirable to avoid arguments based on irregularities in the low percentage contours. It seems best to determine β by configurations of strong maxima. In plot 3 of figure 12 the girdle is drawn through the centers of two maxima. While there is some leeway in drawing this great circle, β for any reasonable fit would fall within the cluster of lineations. In plot 4 the great circle is drawn parallel to the elongation of the single maximum and happens to pass through projections of the 1 per cent contour. Here there is still more leeway in drawing the great circle, but again, any reasonable β will fall within the cluster of lineations and be distinct from β for plot 3. In plot 1 of figure 12 any displacement of β from the center of the projection would certainly be a few degrees to the left of center, in the same direction as the center of gravity of the maximum of lineations in plot 2.

Another question about the interpretation of these diagrams concerns the significance of the original measurements in this particular kind of structure with a vertical β. Measurements of strike probably have a much larger inherent error than measurements of dip for two reasons: (1) with standard geologic compasses measurement of strike to any given precision is much more tedious than measurement of dip, and (2) Cox (1961) has shown that major deflections of the magnetic field are common close to outcrops of volcanic rocks that have been struck by lightning. Thunderstorms and lightning are common in the Sierra Nevada in summer. For either of these reasons there may be a greater variation in strike than in dip, which would produce a vertical β from repeated measurements of a perfectly isoclinal structure. That the vertical β of plot 1 in figure 12 is not the result of such sampling error is indicated because β and lineations vary together in domains on all scales and in some domains they depart appreciably from the vertical.

No structural cross section is presented with this study because, as noted by Sander (1948, p. 71), vertical cross sections cannot depict structure where fold axes plunge steeply. The map is a profile of the steeply plunging structures.

Exceptions to the homoclinal and steeply plunging structure in foliated rocks occur along the east side of the metamorphic belt at Mineral Peak and north of Glacier Pass. Rocks in these areas dip rather gently eastward. An abrupt structural discontinuity separates the gently dipping rocks on Mineral Peak from steeply dipping schists to the west. This discontinuity is marked by a narrow zone of silicification and irregular attitudes. It sharply truncates major folds west of Monarch Lakes. If the contact is approximately planar, its topographic expression indicates that it dips about 30° to the east. This contact marks a change of lithology as well as structure. Lithic layers in the schists above the contact are conspicuously more tabular and less lenticular than the layers in other schists in the area. The contact is probably a thrust fault but might be an unconformity.

Interpretation of Structure

Style and scale.—Styles of structures in the foliated rocks are similar on all scales. Rocks that are lenticular in hand specimens are also lenticular on the scales of large outcrops and the map. In the foliated rocks not only the style of structures but also orientations of fold axes and long dimensions of lenses are the same on all scales. As Dale (Pumpelly, Wolff, and Dale, 1894, p. 158) pointed out long ago, a small specimen in many cases gives the key to a much larger structure. In the present study, styles of mesoscopic structures provide the basis for understanding relations between the macroscopic structure of bedded rocks and that of foliated rocks.

Cleavage and transposition of bedding.—Cleavage is a surface of slip along which transected beds are displaced. In foliated rocks cleavage is the mechanically active slip surface, whereas bedding is a mechanically inactive form surface. Initial folding of bedding rotates limbs of folds toward the axial planes. Slip on cleavage disrupts folded beds, fragments of which continue to be flattened and rotated toward the axial plane. Flattened fragments of disrupted beds ultimately form lenticular lithic layering, subparallel to cleavage. The result of isoclinal folding and slip on cleavage is transposition of bedding into a planar secondary layering that provides no direct evidence of the folding because the folded form surface, bedding, is obliterated. Lineations formed by biotite trains or elongate argillaceous patches on cleavage are relics of bedding-cleavage intersections (see figs. 3 through 7 and accompanying discussion). Orientations of small folds are controlled by the same intersections (see fig. 6 and discussion). Lithic layering has no stratigraphic significance in terms of either sequence or thickness.

The extent to which cleavage and foliation develop is at least in part dependent on rock type. Carbonate and micaceous rocks are incompetent and readily develop foliation; micaceous rocks, however, are more competent than marble—e.g., slate layers in marble are brecciated. Calc-silicate and siliceous rocks are the most competent, and they are rarely foliated. The presence of sharply defined, closely spaced, mechanically effective bedding may retard development of cleavage; northwest of Bullfrog Lake thin-bedded arenaceous and argillaceous rocks are isoclinally folded, without cleavage, whereas bedding in the overlying, thick-bedded and more argillaceous rocks is disrupted and in places obliterated by slip on cleavage (see fig. 11).

In rocks that can recrystallize to form platy minerals, cleavage is probably formed by parallel preferred orientation of micas. Weiss (1955) described a rock in which the preferred orientation of micas defines a plane which intersects the prominent compositional layering in a quartz-mica schist, but is not itself visible in the hand specimen. Corrugations on the layering are parallel to the intersection of this plane with the layering. Weiss suggested that the statistically defined plane is a slip surface. Rocks from the Mineral King area are generally more micaceous than the example described by Weiss. A large amount of mica oriented obliquely to the prominent layering should cause the rocks to cleave across the layering. Lineations produced by intersection of layering with cleavage should be compositional streaks on cleavage rather than corrugations on the layering.

Abundance of published petrofabric diagrams which show the maxima of poles to the micas not perpendicular to the prominent layering, or S, indicates that the relations described above are not rare.

Disharmonic folding.—Styles of mesoscopic and macroscopic structures indicate disharmonic folding on all scales, particularly in the foliated rocks. Sandstone beds have been ripped into rods with lenticular cross sections by slip on cleavage (fig. 6). Laminations within the rods folded by slip on bedding (fig. 3) whereas the surrounding rocks deformed by slip on cleavage. The contact between sandy and slaty rocks thereby becomes a small-scale surface of *décollement* which separates contrasting kinds of rocks with contrasting competencies and different mechanisms of deformation. Similarity of style of the fabric of foliated rocks on all scales indicates that contacts between larger lenticular masses, including mappable units, are also surfaces of *décollement.* Mappable units undoubtedly have been modified or disrupted by the same processes of transposition as have beds within the units. Because contacts between lenticles in hand specimens and contacts between units shown on the map were both rotated toward cleavage, lithologic layering parallels major contacts and may therefore be mistaken for bedding. Neither lithologic layering nor major contacts are folded. The end product of this deformation is a lenticular isoclinal structure that is without direct evidence of major folding because folded form surfaces are obliterated (see upper part of fig. 11). Lithologic units are folded internally, but adjacent units are not generally folded together. Disharmonic folding, with extensive slip on contacts on all scales, further obscures major folds that existed before folded form surfaces were obliterated by transposition of bedding.

Thickness of the metamorphic section.—Knopf and Thelen (1904, p. 243) measured a thickness of 6,090 feet of foliated rocks at Timber Gap. Because bedding in these rocks has been transposed, the measurement does not reflect the original thickness of a corresponding stratigraphic section. Not only is bedding transposed, but structural repetitions of sequences are obscured by disharmonic folding and lack of distinctive beds. In addition, recrystallization and shearing have differentiated units which might originally have been lithologically identical. A gross repetition of units is suggested by the symmetry of distribution of metasedimentary and metavolcanic rocks on either side of the center line of the metamorphic body, although in detail the rocks differ from side to side. Maximum thickness of the metamorphic series, obtained by measuring the maximum width of the metamorphic body and correcting for average dip, is about 12,000 feet. Probable limits of the original stratigraphic thickness are 3,000 to 6,000 feet. Reconstruction of the preorogenic basin configuration of this area from such data is obviously speculative.

Origin of lineations.—Lineations in the foliated rocks at Mineral King are formed by intersection of cleavage with bedding or relics of bedding (see pp. 169 to 178). The orientations of these lineations are geometric consequences of relative orientations of bedding and cleavage, and independent of movements on either surface. The lineations were formed either (1) in their present orientations or (2) in different orientations from which they were rotated to their present ones. Possible mechanisms of rotation of linear elements and the geometry to be anticipated

from rotations have been discussed by Weiss (1959, pp. 98–102). The orientations of lineations shown in figure 12 do not correspond to any of these possibilities. It therefore seems highly probable that the lineations were formed with their present orientations.

If the lineations were formed with their present orientations, it follows that bedding was nearly vertical at the time they were formed; therefore, cleavage formed after bedding dipped vertically. Not only did bedding in the foliated rocks dip steeply at the time cleavage formed, but it probably formed isoclinal folds similar to those now seen in the bedded rocks. This conclusion is suggested by the pattern of distribution of foliated rocks, as seen on the map, which is similar to that of bedded rocks, indicating that the primary stratification of both kinds of rocks was initially deformed in the same pattern. Therefore, although major folds cannot be detected in the foliated rocks, it seems highly probable that the foliated rocks, like the bedded rocks, were isoclinally folded about subhorizontal axes and that the folded stratification has subsequently been obliterated.

A hypothetical structural evolution of the foliated rocks may be suggested: Primary stratification of the rocks that are now foliated was initially folded about subhorizontal axes. After these folds became approximately isoclinal, cleavage formed with a mean orientation parallel to the axial planes of the early folds. The axis of cleavage orientations, however, was vertical, approximately perpendicular to the fold axes (fig. 13). Lineations formed by intersection of bedding with cleavage. The vertical maximum of lineations reflects a predominantly vertical orientation of limbs of the isoclinal folds. The spread in orientations of lineations is due to variation in relative orientation of bedding and cleavage. Bedding was obliterated by slip on cleavage. Traces of it remain as lithic lenticles and compositional streaks on cleavage in the foliated rocks.

Horizontal intersections of bedding and cleavage should be expected in hinge areas of the earlier folds. The lack of such horizontal lineations may be explained by three things: (1) cross sections of mapped folds are nearly isoclinal and have only a small percentage of their areas in the hinges; (2) beds commonly break in the hinges and lie parallel to the axial surface, providing no area for horizontal intersection (see fig. 7); and (3) where beds do swing around the hinge, bedding surfaces become so indistinct that the rock has no well-defined planes with which to form lineations by intersection with cleavage.

Kinematic interpretation.—Lineations in the rocks at Mineral King are formed by intersections of surfaces, have no direct kinematic significance (see Weiss, 1955, p. 228), and cannot be used for kinematic interpretation of the structure. That the lineations are not produced directly by movements on surfaces is further indicated by lack of lineations in isoclinally folded, bedded rocks that are devoid of cleavage, even though folding must have involved extensive slip on bedding surfaces. An alternative basis for kinematic interpretation is the geometry of structural surfaces, i.e., cleavage. A kinematic interpretation based on this geometry is analogous to kinematic interpretation of structures in stratified rocks based on geometry of faults; intersections of bedding with fault planes have no direct kinematic significance but angular relations among faults are significant. The cleavages at Mineral King, indeed, are microscopic faults which distribute movements more or less uniformly through the body of the rocks.

Cleavage at Mineral King is observed to consist of nearly parallel, complementary slip surfaces that are inferred to be nearly perpendicular to the least deformation axis (or axis of greatest shortening) as suggested by Sander (1930), Washburne (1940, p. 715), and Hills (1953, pp. 38, 106), and experimentally produced by Oertel (1955). The reasons for this inference are: (1) the mean orientation of cleavage is parallel to axial surfaces of folds; (2) orientations of cleavage, plotted

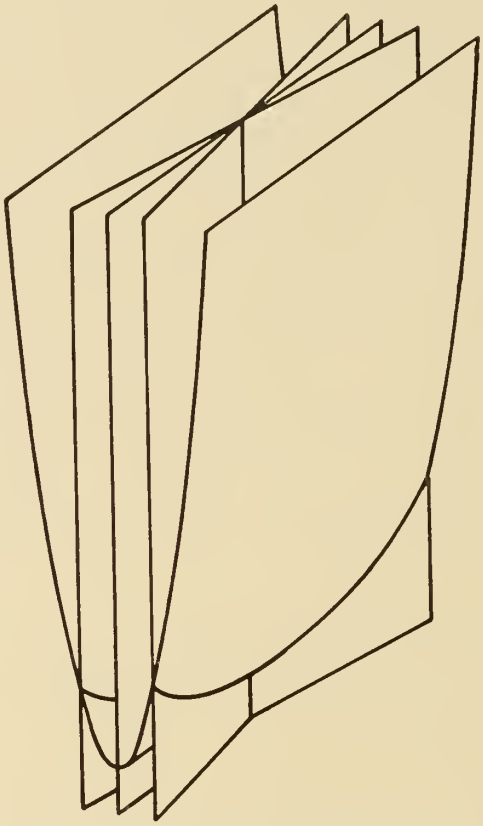

Fig. 13. Schematic diagram of the relation between folded axes and cleavage axes.

on equal area projections, vary through angles of 10° to 20° and intersect in vertical axes; (3) cleavage is a surface of slip; and (4) forms of surfaces that are offset across cleavage indicate that complementary senses of slip occur on subparallel cleavages (see figs. 2, 5 and pl. 2, *a*). Forms of blurred surfaces in slaty rocks suggest deformation of the folded form surface by laminar slip on cleavage. Carey (1953) discussed geometric consequences and geologic examples of deformation by laminar flow.

In a common model of deformation, complementary slip surfaces intersect in the intermediate deformation axis, perpendicular to the directions of slip on either surface. Slip on cleavage at Mineral King is inferred to have been directed transverse to the statistically vertical axis of cleavage intersections, hence parallel to the strike of cleavage.

The inferred sequence of movements is: (1) during initial folding of strata slip occurred on mechanically active bedding surfaces, transverse to subhorizontal fold axes; (2) after cleavage formed, strike-slip movements occurred on cleavage. These strike-slip movements produced some large-scale rotations, as shown by the vertically plunging fold in foliated rocks north of Franklin Creek. Large-scale strike-slip translations disrupted units and destroyed any systematic repetitions of strata that might have been produced by the initial folding.

Local deviations of the cleavage axis from vertical may indicate local variation in the pattern of movement but need not do so. Linear structures are produced by intersection of bedding with cleavage. Slip on either set of surfaces would rotate the other set about the line of intersection, independent of the sense of slip (Weiss, 1955, p. 228). If any slip at all occurred on bedding or lithic layering after cleavage formed, cleavage would be rotated about the line of intersection. The close parallelism of cleavage axes and lineations in various structural domains in the foliated rocks (see p. 180 and fig. 12) suggests that some slip did take place on bedding or lithic layering after cleavage formed. Local deviation of the cleavage axis from vertical, therefore, is not necessarily inconsistent with strike-slip movements throughout.

This kinematic interpretation is essentially two dimensional, but it would be surprising if the deformation described here were a plane deformation. Shapes and orientations of deformed pebbles provide some evidence of deformation in three dimensions. Unfortunately, mechanisms of plastic deformations of solids—and hence kinematic significance of elongations—are not known. Cloos (1947) has described oölites elongated perpendicularly to fold axes, whereas White and Jahns (1950, p. 204), Flinn (1952), and Elwell (1955) have described pebbles elongated parallel to steeply plunging lineations and small folds. Perhaps the entire rock mass elongated vertically. Movements in the foliated rocks, then, might have been, (1) flattening along a line perpendicular to the mean orientation of cleavage, by strike-slip movements on cleavage, and (2) vertical elongation along the axis of slip surfaces. This kinematic interpretation is inferred from geometries of structures on mesoscopic and macroscopic scales. The geometric description is incomplete because structural geometry on a microscopic scale is not known. The kinematic interpretation, therefore, is necessarily tentative.

Movements in granodiorite.—Contact relations suggest that the granodiorite on the west side of the metamorphic body may have been emplaced during the last stages of deformation of the metamorphic rocks. Near Eagle Lake the orientation of structures in the granodiorite is the same as that of structures in the adjacent wall rocks. Similar structural geometry suggests similar patterns of movement, and the granodiorite is inferred to have moved laterally along the contact. Whether or not movements in the metamorphic rocks were produced by emplacement of the granodiorite cannot be established from field relations in this area. A comparison of orientations of metamorphic foliations on the nose at Eagle Lake with those in the rest of the area suggests clockwise rotation about a vertical axis and, hence, lateral forcible intrusion of the tongue of granodiorite to the east. Abundant evidence of mobility of the granodiorite along the contact, combined with a style of structure that markedly contrasts with that in the metamorphic

rocks, indicates that structures in the granodiorite are a result of movements in the pluton and are not inherited through transformation of metamorphic rocks.

Deformation axes and stress axes.—I suggest that the structure of the metamorphic rocks is the result of one deformation. During this deformation the axis of greatest shortening maintained a constant orientation, while the orientation of the axis of greatest elongation varied. Because axial planes of folds on all scales and of all styles are parallel, it is inferred that the rock mass flattened along a line (the least-deformation axis) perpendicular to the axial planes. Orientations of the intermediate- and greatest-deformation axes varied within the axial planes. If the axis of intersection of slip surfaces is taken to be the intermediate-deformation axis, then the intermediate axis was subhorizontal during deformation by slip on bedding and vertical during deformation by slip on cleavage.

This interpretation of deformation axes involves unproven assumptions. To carry on from these kinematic inferences to interpretations of possible stress systems involves further and still more speculative assumptions. Hence the following suggestions constitute only a possible interpretation of the dynamic origin of these structures.

Shearing stresses combined with initial horizontal anisotropy of the stratified rocks controlled initial changes of shape, and hence the geometry of major folds in bedding. It seems probable that the geometry of structural surfaces, which developed after bedding became mechanically ineffective, was controlled by the stress system only. Styles of structures suggest plastic or viscous behavior of the rocks and therefore a high pressure hydrostatic stress system before deformation. A horizontally directed compression introduced into the hydrostatic system defined the axis of greatest stress and the vertical plane of the other two axes which remained equal. Because the initial state was hydrostatic the intermediate- and least-stress axes would not be differentiated at this stage, but horizontal anisotropy of the rocks would result in horizontal fold axes and, consequently, a horizontal intermediate-deformation axis. As deformation proceeded, a vertical intermediate-stress axis might have been produced by either an increase in superincumbent load due to vertical thickening by folding or a decrease in stress parallel to the fold axes due to stretching or bending of the entire fold belt. As bedding became isoclinal and mechanically ineffective, complementary slip surfaces formed nearly perpendicular to the axis of greatest stress and varying in orientation about the vertical intermediate-stress axis. It is entirely possible that the more competent rocks and rocks with mechanically effective bedding continued to fold about horizontal axes while strike-slip movements on cleavage profoundly modified the structure of less competent rocks.

CONCLUSIONS

The presence of cleavage differentiates foliated rocks from bedded rocks in the metamorphic suite. Contrast between the structural geometry of foliated rocks and bedded rocks is the basis for inferring that structures in the foliated rocks reflect movements that did not affect the bedded rocks.

Deformation of the metamorphic rocks began with isoclinal folding of stratified rocks about horizontal axes. This folding established the northwest-striking, verti-

cally dipping pattern of rock units. These folds can be seen in mappable units of bedded rocks.

Continued deformation produced "axial plane" cleavage in the less competent members of the metamorphic suite. Although this cleavage is essentially parallel to axial planes of the earlier folds, orientations of cleavage vary about vertical axes, which are nearly perpendicular to the major fold axes. Intersection of cleavage with bedding produced lineations and small folds. These linear structures plunge steeply because cleavage intersected nearly vertical bedding in steeply plunging lines. Cleavage is a surface of slip. Slip on transecting cleavage disrupted stratification. Fragments of disrupted beds were flattened and rotated, ultimately forming lenticular lithic layering subparallel to cleavage. Lineations formed by biotite trains and argillaceous smears on cleavage are relics of intersection with bedding that has been obliterated. Mappable rock units were disrupted by similar movements on larger scales. Transposition of bedding into lithic layering and disruption of rock units obscured early-formed folds in stratification.

Complementary slips occurred on subparallel cleavage surfaces. The direction of movement is inferred to have been strike-slip, transverse to the vertical cleavage axis. It is inferred that the rock mass shortened along a line perpendicular to cleavage by movements akin to laminar flow on subparallel slip surfaces. Strike-slip on cleavage suggests lateral extension along the strike in foliated rocks. Strain parallel to the cleavage axis is indeterminate.

Several general conclusions are suggested: (1) The structure is subject to gross misinterpretation if lithic layering is mistaken for bedding, because the rocks then appear not to be folded. The lenticular lithic layering is a mechanically produced, compositional layering that has no more stratigraphic significance than does layering produced by chemical metamorphic differentiation. (2) Linear structures at Mineral King have no direct kinematic significance. (3) "Axial plane" cleavage should be classified according to whether the cleavage axis is parallel, inclined, or perpendicular to axes of folded form surfaces, because this relation controls the orientations of structures produced by intersection of bedding with cleavage. (4) In plastic deformations complementary slip surfaces may form nearly perpendicular to the axis of greatest shortening, or to the major stress axis.

COMPARISON WITH OTHER AREAS

Lenticular fabrics and steeply plunging structures are characteristic of foliated metamorphic rocks in the Sierra Nevada. Fabrics similar to those described here have been related by Compton (1955, p. 43) to horizontal expansion of a small pluton. Available data on the geometry of metamorphic structures in the Sierra Nevada have been summarized by Parker (1959).

Similar structures are widespread in the central parts of mountain ranges the world over and in the crystalline roots of inferred ancient mountain ranges. Hawkes (1941, p. 648) reported steeply plunging linear structures in the foliated, homoclinal, steeply dipping Green Mountain sequence in the northern Appalachians, and inferred that these structures were produced by strike-slip movements. P. B. King (oral communication) reports steeply plunging small folds in the slate belt in Maine. I have seen lenticular fabrics in steeply plunging structures in the Vishnu schist in Grand Canyon.

The problems of steeply plunging structures have long been recognized in Europe. This style of structure has been graced with the name *Schlingentektonik* and is of general enough occurrence to be discussed in introductory textbooks in structural geology (Metz, 1957, p. 42). In the Alpine chain Sander and his students have studied Austrian *Schlingentektonik* for years, and recently Kvale (1957) has described examples from the synclines near the Gotthard massif in Switzerland. Steep-axis structures also occur in the Caledonian chain, and examples from Scotland have recently been described by Knill and Knill (1958). Farther afield, Sander (1948, p. 208) mentioned steep-axis structures in the Karakorum Himalaya. *Schlingentektonik* is a characteristic feature of deformation in orogenic belts, and understanding of the origin and kinematic significance of this style of structure must precede any general synthesis of orogenic processes.

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PLATES

a. Calc-silicate hornfels. Relic bedding tightly folded and disrupted on nose of larger fold.

b. Calc-silicate hornfels. Relic bedding transposed into lenticular lithic layering on limb of same fold as in *a*.

a. Sandstone hornfels. Bedding offset by slip on cleavage on nose of fold. Note in left center of photo: two cleavage surfaces which diverge about 20° have opposite senses of slip. These surfaces intersect in a line parallel to the axis of this fold and perpendicular to the surface of the exposure, which is an "a–c" joint.

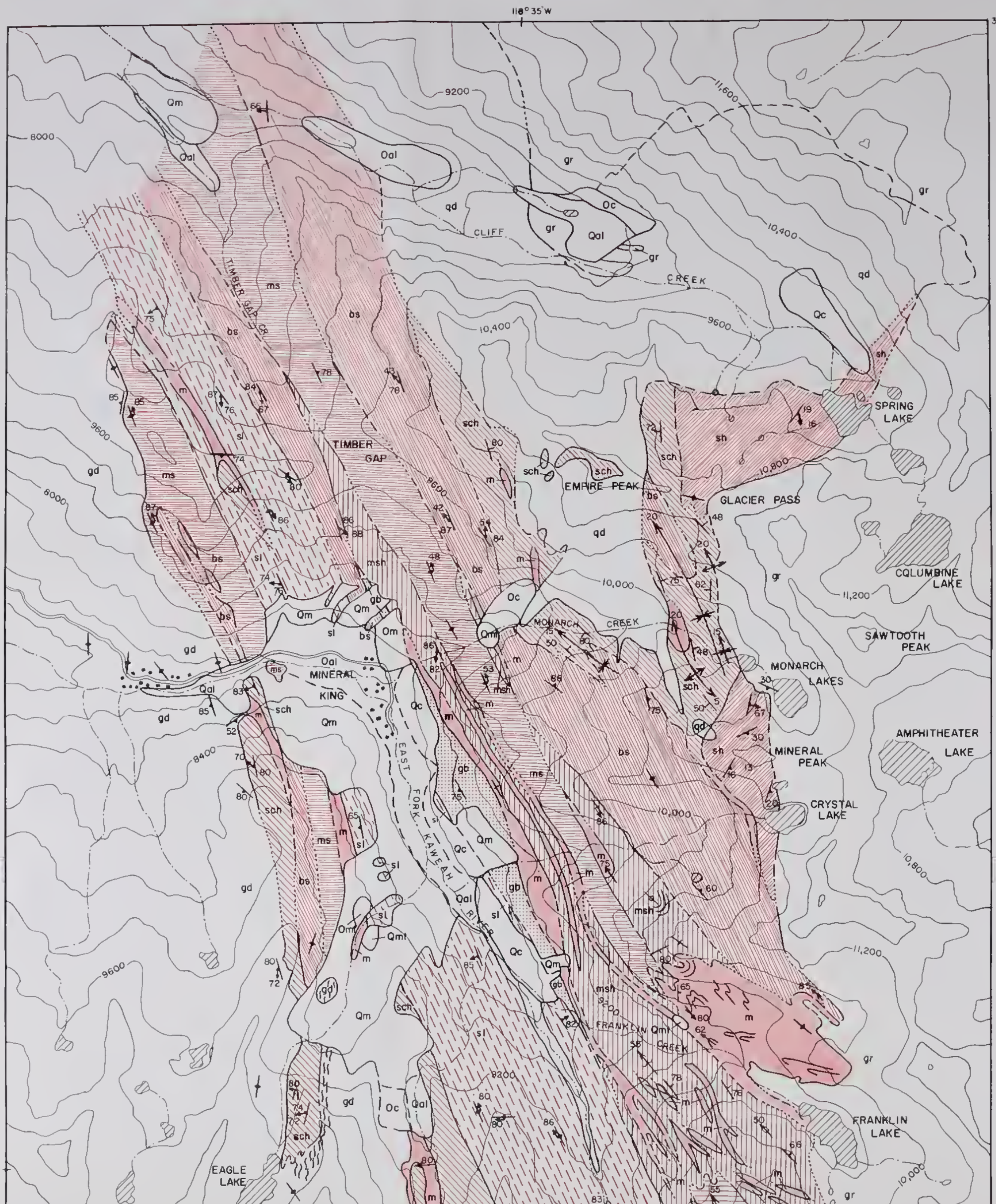
b. Sandstone hornfels. Relic bedding transposed into lenticular lithic layering on limb of the same fold as in *a*. Glacial striations cross the trace of the layering.

a. Metachert with slate partings. Chert beds are disrupted where slate partings are thick. Limb of fold sheared off at lower left.

b. Metachert. Chert beds transposed into lenticular lithic layering parallel to axial planes of adjacent folds, like that in *a*.

a. Augen mylonite. Lenticular lithic layering produced by transposition of bedding in slate and sandstone.

b. Marble. Disrupted calc-silicate beds form lenticular lithic layering.



EXPLANATION

UNCONSOLIDATED DEPOSITS

- Oal — Alluvium
- Qmt — Terminal moraine
- Qm — Undifferentiated moraine
- Oc — Colluvium
- msh — Massive to thick-bedded sondstone ond argillite hornfelses interbedded with marble
- bsh — Thin-bedded sondstone and siltstone hornfelses
- sch — Siliceous and calc-silicote and pelitic harnfelses

METAMORPHIC ROCKS

- m — Marble
- sl — Slate, phyllite & sheared sandstone
- ms — White-mico schists
- bs — Plagioclase-biotite schist
- sh — Plagiaclose-biotite schist intercalated with aluminous hornfels
- gb — Gabbra

PLUTONIC ROCKS

- qd — Quartz diorite
- gd — Granodiorite, in port sheored
- gr — Granite

- Contact, dashed where approximately located, datted where hidden
- 70 — Strike and dip of bedding
- 80/45 — Strike and dip of foliation, frend plunge of lineor structure
- Vertical foliation
- 80 — Smoll fold, orraw indicales frend and plunge of oxis, curve indicoles sense of clasure and strike of axial plane
- Vertical fold with strike of axial plane
- 20 — Trace of oxiol plane of upright anticline, plunge of axis
- 20 — Troce of axial plane of upright syncline, plunge of axis

Topography by U.S.G.S., 1956

Geology by M.N. Christensen, 1956, 1957, 1958

GEOLOGIC MAP OF THE MINERAL KING AREA, CALIFORNIA

1 0 1 2 3 Miles

Contour Interval 400 Feet

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